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EFFECTS OF A SIMULATED HIGH ENERGY ELECTRON SPACE ENVIRONMENT ON THE ULTRAVIOLET TRANSMITTANCE OF OPTICAL MATERIALS BETWEEN 1050 AND 3000 A

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ABSTRACT

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Transmittances from 1050 - 3000A of LiF, MgF_2, CaF_2, BaF_2, Al_2O_3 and fused SiO_2 are given before and after irradiation by 10^{14} e/cm^2 at 1.0 and at 2.0 mev. Similar measurements were made with 10^{14} e/cm^2 at 2.0 mev using Al_2O_3 to shield fused SiO_2, ADP, calcite, and Corning filters 9-54 and 7-54 from the direct electron beam.

Author

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I INTRODUCTION

In recent years there has been considerable interest in the behavior of optical materials in the hostile environment of space. The term "optical degradation" is sometimes used to explain discrepancies between predicted and observed results for space optical experiments. It is the purpose of this work to investigate the effects on transmittance of optical materials for ultraviolet use when subjected to irradiation by high energy electrons. The amount of irradiation is determined by what one might expect to encounter for a period of one year in space for a given orbit. This work is restricted to materials which are transparent in the region from 1050 to 3000A.

It is true that much work has appeared in the literature of solid state physics on the effects of high energy irradiation of optical crystals and glasses. Unfortunately the dose of irradiation is usually much larger than one would expect to encounter in an earth orbit of one year duration. This is done deliberately to introduce large numbers of crystal defects and color centers. Furthermore most of the work has been restricted to the non-vacuum region above 2000A.

The materials studied in this work were divided into two groups. The first group composed of LiF, MgF_2, CaF_2, BaF_2, Al_2O_3 and fused SiO_2 were placed directly in the high energy electron beam. The second group composed of fused SiO_2, ADP, calcite, andCorning filters 9-54 and 7-54 were shielded from the direct electron beam by an Al_2O_3 crystal. The principle irradiation for this group is the bremsstrahlung resulting from stopping the electrons in the sapphire crystal.

II ELECTRON ENERGY DISTRIBUTION IN SPACE

The Starfish explosion (1.4 megatons) at 400 km above Johnston Island in July 1962 produced a slowly decaying artificial electron belt. At about 1000 km, the electron energy distribution closely resembled a fission energy spectrum (β-decay from fission fragments). With the passage of time the energy spectrum will be modified by scattering. It is not too unreasonable to simulate the artificial electron belt by irradiating with electrons in the 1-2 mev region.

Calculations by the Laboratory for Theoretical Studies at G. S. F. C. show that by January 1968, 95% of the artificial electrons from Starfish should have energies less than 3 mev, and 71% less than 1 mev for a circular, near polar orbit at 1200 km. For January 1966 in a circular near polar orbit at 1400 km, the predicted maximum flux would be 10^{14} e/cm^2/yr if there were no decay.

III EXPERIMENTAL PROCEDURE

The transmittances were measured at the exit slit of a one meter, McPherson Model 225 monochromator using a Hintereggar type windowless hydrogen light source. A sample holder was constructed which made it possible to either insert or remove the crystal from the exit beam without breaking the vacuum.

The crystals listed in Table I were irradiated with 10^{14}/cm^2 electrons at 1.0 mev and then with 10^{14}/cm^2 electrons at 2.0 mev. Irradiation times were 30 minutes at each energy.

The synthetic sapphire (α - $A/_2 O_3$) showed the smallest change in transmittance due to electron irradiation. Hence it was used as an electron shield for the materials listed in Table II. The 6.4 mm thick Al_2O_3 crystal was placed between the incident 2.0 mev beam and the crystal being irradiated. In a space experiment this would correspond to using a sapphire shield to stop the majority of the high energy electrons in the radiation belt. In this case the principal source of irradiation would be the resulting bremsstrahlung. The total irradiation came from 10^{14} e/cm^2 at 2.0 mev incident on the sapphire window. No attempt was made to shield the materials listed in Table II from scattered electrons.

All measurements of transmittance were made within a few hours after irradiation. Furthermore phosphorescence was detected in all irradiated crystals, although it could not be observed visually. Corrections were made for this light emission in the measurements of transmittance.

IV TRANSMITTANCE CHANGES FROM ELECTRON IRRADIATION

Lithium Fluoride

The sample measured was an optically polished high purity synthetic crystal made by the Harshaw Chemical Co. The transmittance before and after irradiation is given in Figure 1. Obviously LiF is a poor candidate for use in space optics in a high energy radiation environment. Even though the crystal has turned bright yellow there is a band which remains slightly transparent from 1200 to 1650A. For the important solar hydrogen Lyman alpha at 1216A the transmittance has decreased from 60% to 2%. Beyond 2800A it begins increasing rapidly up to 33% at 3000A. For detailed information on the radiation induced absorption features in the far ultraviolet see the work of Uchida et al[2].

These absorption features can be bleached out by heating to 400° C for several hours. Unfortunately, at present, the power necessary to do this on an earth satellite would be a practical limitation.

Magnesium Fluoride

The sample used was a high purity crystal grown and optically polished by the Harshaw Chemical Co. It only has been within the past few years that MgF_2 crystals have been available which transmit below 1300A. From Figure 2 it can be seen that the crystal begins transmitting at 1130A, and that it has a transmittance of 52% at hydrogen Lyman α. Under electron irradiation two distinct absorption bands develop. The strongest absorption band is at 2600A while a considerably weaker one is definitely present at 1200A. The band at 2600A is a well known feature. See for example the work of Duncanson and Stevenson[3] on the properties of MgF_2 crystallized from the melt.

Even with this weak radiation induced absorption feature at 1200A, the transmittance at Lyman alpha has decreased only from 52% to 36%. This is certainly a very modest reduction when compared to the factor of 30 reduction in transmittance in LiF in the same radiation environment.

Magnesium Fluoride has the added advantage of being considerably less soluble in water than LiF. (.013 vs 0.27 g/100g of H_2O) Note also that no change in transmittance is observed in the 1300 - 1600A region.

Calcium Fluoride

This synthetic crystal was polished in the optical shop at G. S. F. C. The source is the Harshaw Co. Under electron irradiation the sample developed a strong violet color. From the transmittance curves of Figure 3 it can be seen that the effects of irradiation are least pronounced in the vicinity of the short wavelength limit. As one goes to longer wavelengths the absorption becomes stronger. Two distinct absorption features occur at 1900A and 2250A. It appears that another is developing as one approaches 3000A. This is probably the α band at 3700A[4].

Barium Fluoride

This crystal appears to be highly radiation resistant except for a small amount of absorption around 2500A as can be seen in Figure 4. Barium fluoride may be useful not only as a filter material but also as a low index of refraction element of an achromat for the vacuum ultraviolet.

The curves in figure 4 are at variance with the work of Messner and Smakula[5] on the absorption of BaF_2 colored by 3 mev electrons at 20° C. They show a major absorption band at 2000A, but only a very minor one at 2500A.

Sapphire

Transmittance curves are given for three conditions in Figure 5 for Linde polished ultraviolet grade synthetic sapphire (α-Al_2O_3). The curves are given for the following cases: unirradiated, 10^{14} e/cm^2 at 1.0 mev plus 10^{14} e/cm^2 at 2.0 mev, and for a total dose of 2 x 10^{14} e/cm^2 at 1.0 mev and 7 x 10^{14} e/cm^2 at 2.0 mev. The only observed losses in transmittance are possibly a small decrease at 2600A and beyond 2950A. The weak absorption at 2600A and the slight decrease above 2950A may correspond to induced absorptions by reactor irradiations at 2554 and 3000A as reported by Levy[6].

Strangely enough the very well known strong absorption band at 6.06 ev (2040A) is not observed. One observes at this energy instead of increasing absorption, increasing transmittance with increasing electron irradiation. This phenomena, an increase in transmittance with irradiation has been observed by Levy[6] in the lower energy region of 3 to 1 ev.

From these measurements one may conclude that synthetic sapphire is highly resistant to high energy electron irradiation such as one encounters in the lower regions of the radiation belts. Hence Al_2O_3 should be useful for shielding more radiation sensitive optical elements which transmit in the 1450 - 3000A region from the electron space environment. Synthetic sapphire might also be useful as the high index element with BaF_2 as the low index element in an achromat for use in the 1450 - 3000A region.

Fused Silica

Whereas the sample of Al_2O_3 remained relatively unaffected by electron irradiation in the ultraviolet but became slightly beige in color, the sample of high purity fused silica (Dynasil Optical Grade) remained perfectly clear while undergoing a considerable change in transmittance below 3000A. This is clearly seen in Figure 6.

The most prominent radiation induced feature is the C band at 2150A. Even though it is not too obvious one can see that the radiation induced absorption coefficient increases as one goes to wavelengths below 1800A. The maximum appears to lie between 1670A and the cutoff at 1600A. This is the E band. Nelson and Weeks[7] have shown that synthetic crystal quartz is more resistant to the production of the C band whereas the E band is produced equally readily in either crystal quartz of fused silica.

From these measurements it is apparent that great caution should be taken if one uses fused silica in a high energy electron environment to transmit wavelengths below 2800A.

V TRANSMITTANCE CHANGES IN ELECTRON SHIELDED MATERIALS

From the measurements made on the crystals listed in Table I it is concluded that synthetic sapphire is the best choice for shielding the more radiation sensitive elements from high energy electrons. For the materials listed in Table II, the 6.4 mm thick synthetic sapphire was placed between the 2 mev electron beam and the particular sample being irradiated. The total dose for each sample was 10^{14} e/cm^2 at 2.0 mev incident on the sapphire.

Fused Silica

Two high purity samples were measured. These were Corning 7940 and Dynasil 1850A. The transmittance curves in Figures 7 and 8 show some evidence of having increased after irradiation in the region from 1800 - 1950A. This effect is very close to the accuracy of the measurements and may not be real, although it is rather surprising that it appears in both samples. From these measurements it appears that fused silica can be used as an optical element in space if it is properly shielded from high energy electrons.

ADP

This ammonium di-hydrogen phosphate was a crystal grown and polished by the Harshaw Chemical Co. This crystal has an extremely sharp ultraviolet cutoff at 1800A and it shows practically no change in transmittance after being irradiated as can be seen in Figure 9. There is the possibility that there is a very small amount of radiation induced absorption between 1850 and 2050A. However, the conclusion is that ADP is useful for space optical uses below 3000A.

There are difficulties in using this crystal. It is fairly hygroscopic, and it is very sensitive to thermal shock. It was quite warm after irradiation and when it was picked up at the edges, it fractured.

Calcite

The crystal is of high optical quality and was optically polished by the Harshaw Chemical Co. No radiation induced absorption is observed in the transmittance curves in Figure 10. Therefore calcite when properly shielded from electrons is suitable for space use.

Corning 9-54

This is the familiar Vycor (7910), a high silica content glass. Visually the sample turned grey. From Figure 11 it can be seen that the transmittance is strongly affected below 3000A. Hence one should be very cautious about using it in space for extended periods.

Corning 7-54

This familiar black ultraviolet transmitting glass darkened rapidly in the radiation environment as can be seen in Figure 12. This Corning glass (9863) is known to darken upon exposure to intense ultraviolet radiation. This is a very poor material for optical use in space.

VI CONCLUSIONS

It was the purpose of this work to investigate the effect on transmittance of a standard high energy electron environment on a number of optical materials which transmit in the 1050 - 3000A region.

Of the materials listed in Table I, MgF_2, BaF_2 and Al_2O_3 appear to have the greatest potential for space applications. Magnesium fluoride should prove to be especially valuable because of its high transmittance at hydrogen Lyman alpha as well as its birefrigence. Polarizers have been made for the vacuum ultraviolet utilizing MgF_2 .[8]

Barium fluoride and synthetic sapphire might be useful as elements in an achromat. However, care must be exercised in its use. Recent work by Malitson [9,10] et al. shows that not only are there radiation effects on transmittance but also on the index of refraction. Unfortunately the indices of refraction of most ultraviolet transmitting materials are poorly known.

All the materials except Corning glasses 9-54 and 7-54 appear to be suited for space use if the proper precautions are taken to shield them from direct electron irradiation in space. The crystals, ADP and calcite, which are birefringent would be useful as ultraviolet polarizers.

VII ACKNOWLEDGMENTS

We would like to acknowledge the Harshaw Chemical Company for samples of MgF_2, the Corning Glass Company for samples of 9-54 and 7940 fused silica, the Astrophysics Branch at GSFC for samples of BaF_2 and 7-54, the Dynasil Corporation for fused SiO_2, and Mr. Steve Olfky of the W.R. Grace Co. for his assistance in the electron irradiations.

Table I

Crystal	a	b	c	d	e
LiF	1050A	2.09 mm		1050 - 1200A, and 1650 - 2800A	yellow
MgF_2	1130A	1.51 mm	90°	1200A, 2600A	colorless
CaF_2	1230A	3.60 mm		1900A, 2250A	violet
BaF_2	1335A	1.10 mm		2500A	blue tint
Al_2O_3	1435A	6.41 mm	60°	2050A*, 2650A, > 2950A	beige
SiO_2	1595A	6.46 mm		1650A, 2150A	colorless

[a] Ultraviolet transmission limit
[b] Thickness
[c] Angle of c axis with electron beam for birefringent crystals
[d] Radiation induced absorption features
[e] Color after irradiation

*Transmittance increases with irradiation

Table II

Crystal	1580A	b	c	d	e
SiO_2 (Corning)	1580A	3.29 mm		1900A*	colorless
SiO_2 (Dynasil)	1590A	2.94 mm		1900A*	colorless
ADP	1780A	2.99 mm	0°	1900A?	colorless
Calcite	2030A	2.25 mm	45°	none	colorless
Corning 9-54	2185A	2.22 mm		all	grey
Corning 7-54	2270A	3.02 mm		all	black

[a] Ultraviolet limit of transmission
[b] Thickness
[c] Angle of c axis with electron beam for birefringent crystals
[d] Radiation induced absorption features
[e] Color after irradiation
* Transmittance increases with irradiation

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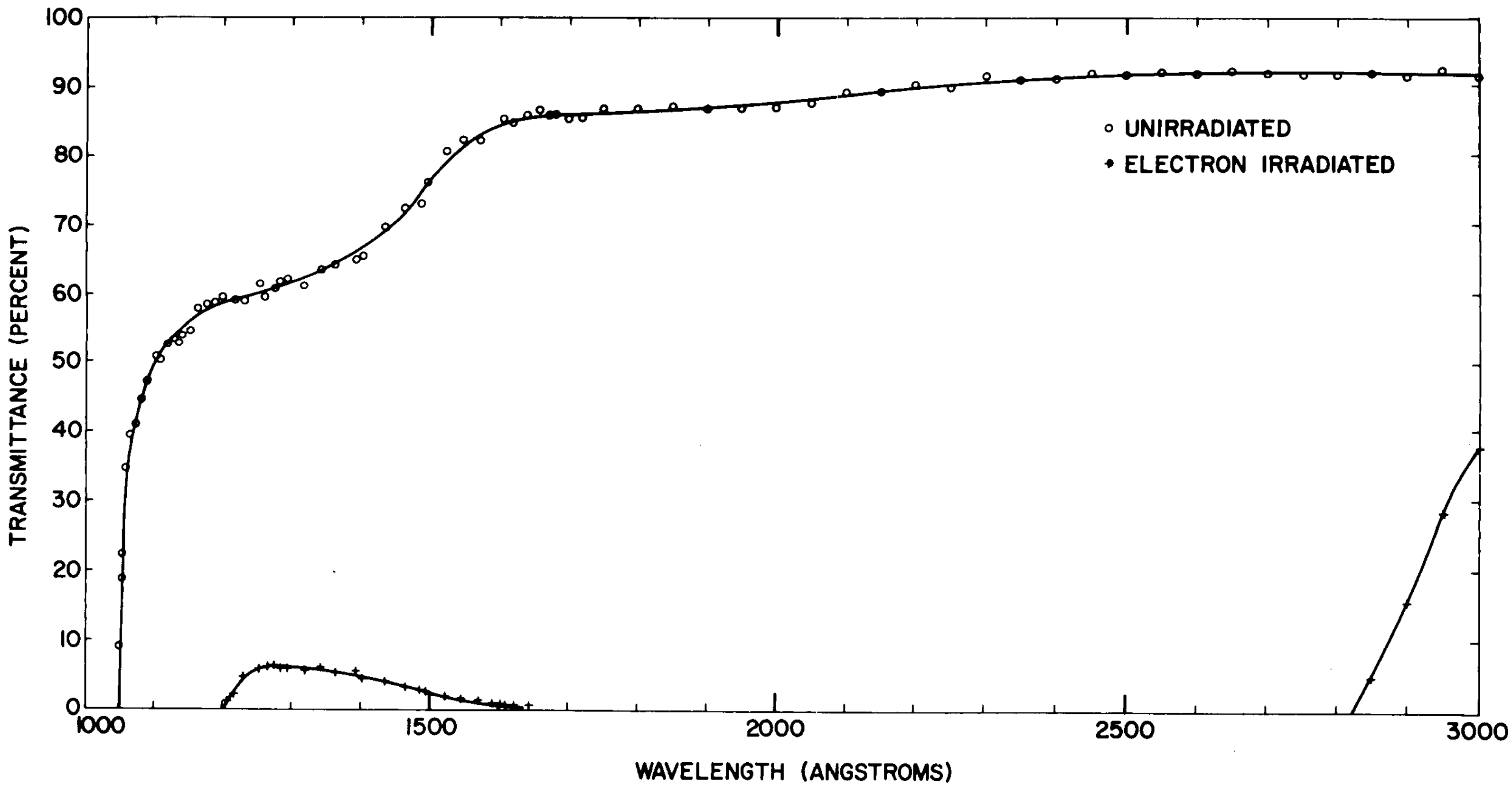

Figure 1—Transmittance of LiF before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev and at 2.0 mev

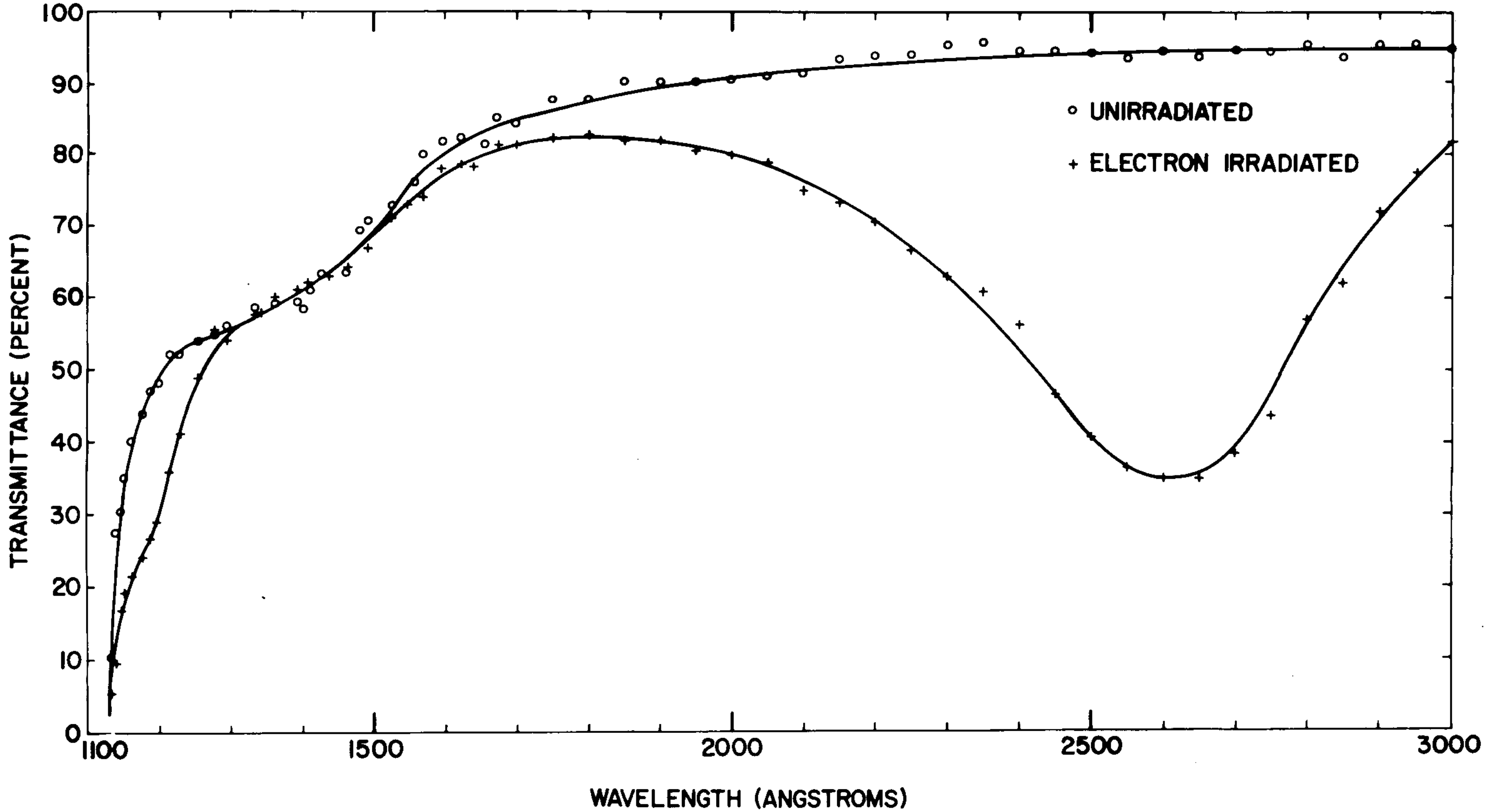

Figure 2–Transmittance of MgF_2 before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev and at 2.0 mev

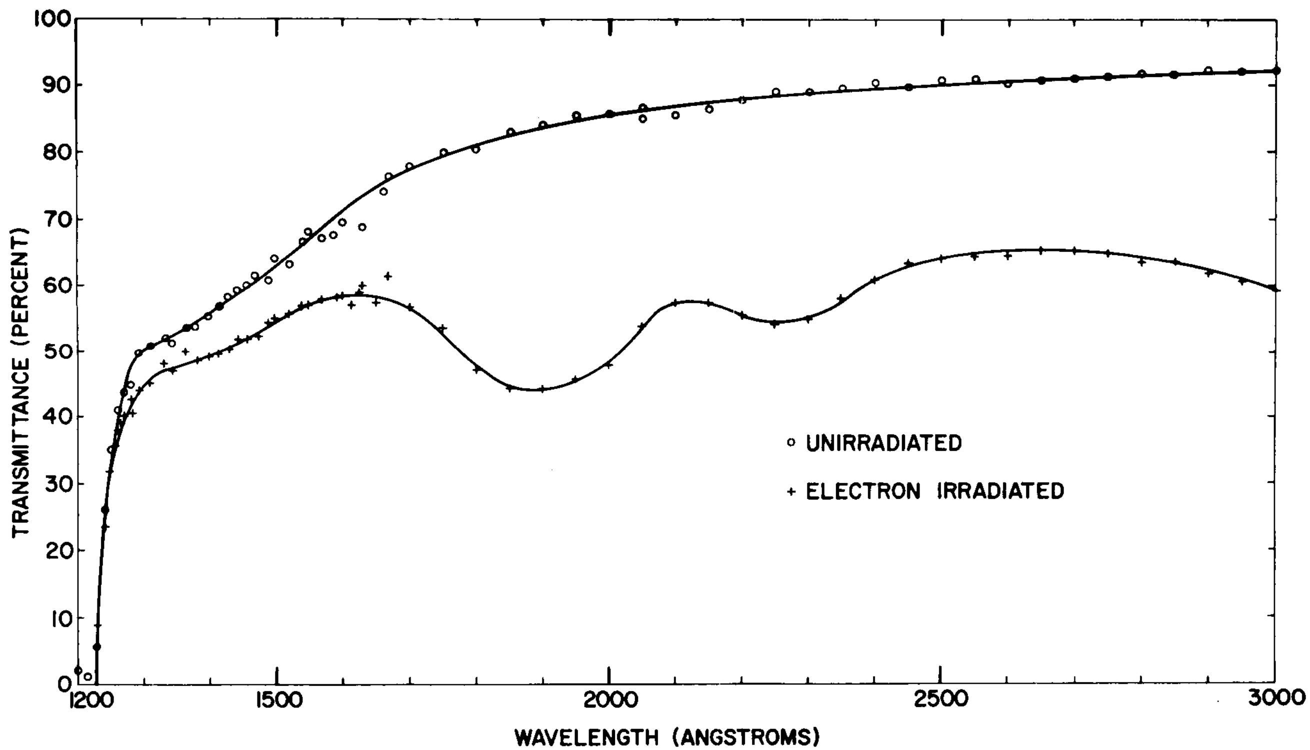

Figure 3–Transmittance of CaF_2 before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev and at 2.0 mev

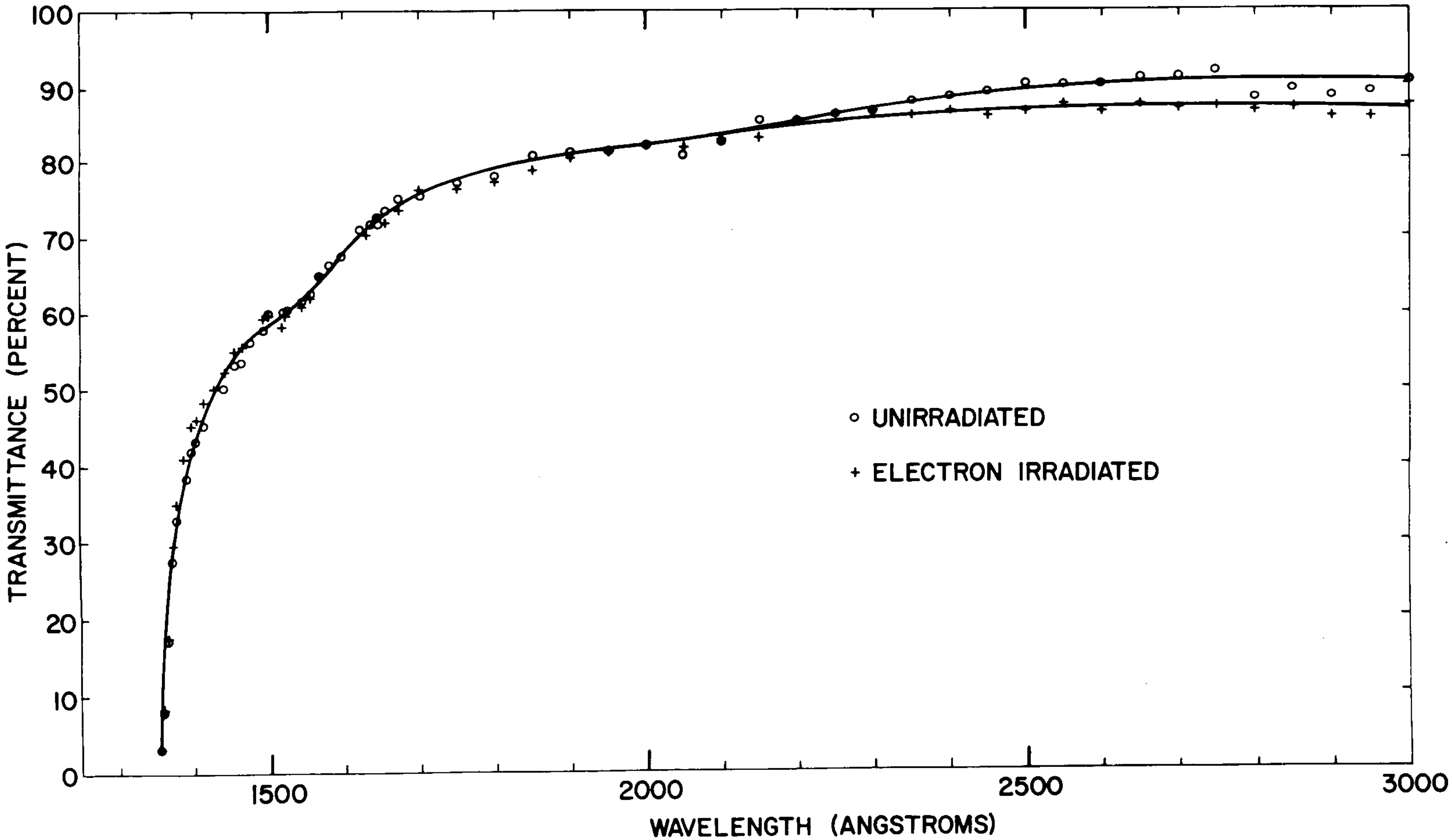

Figure 4–Transmittance of BaF_2 before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev and at 2.0 mev

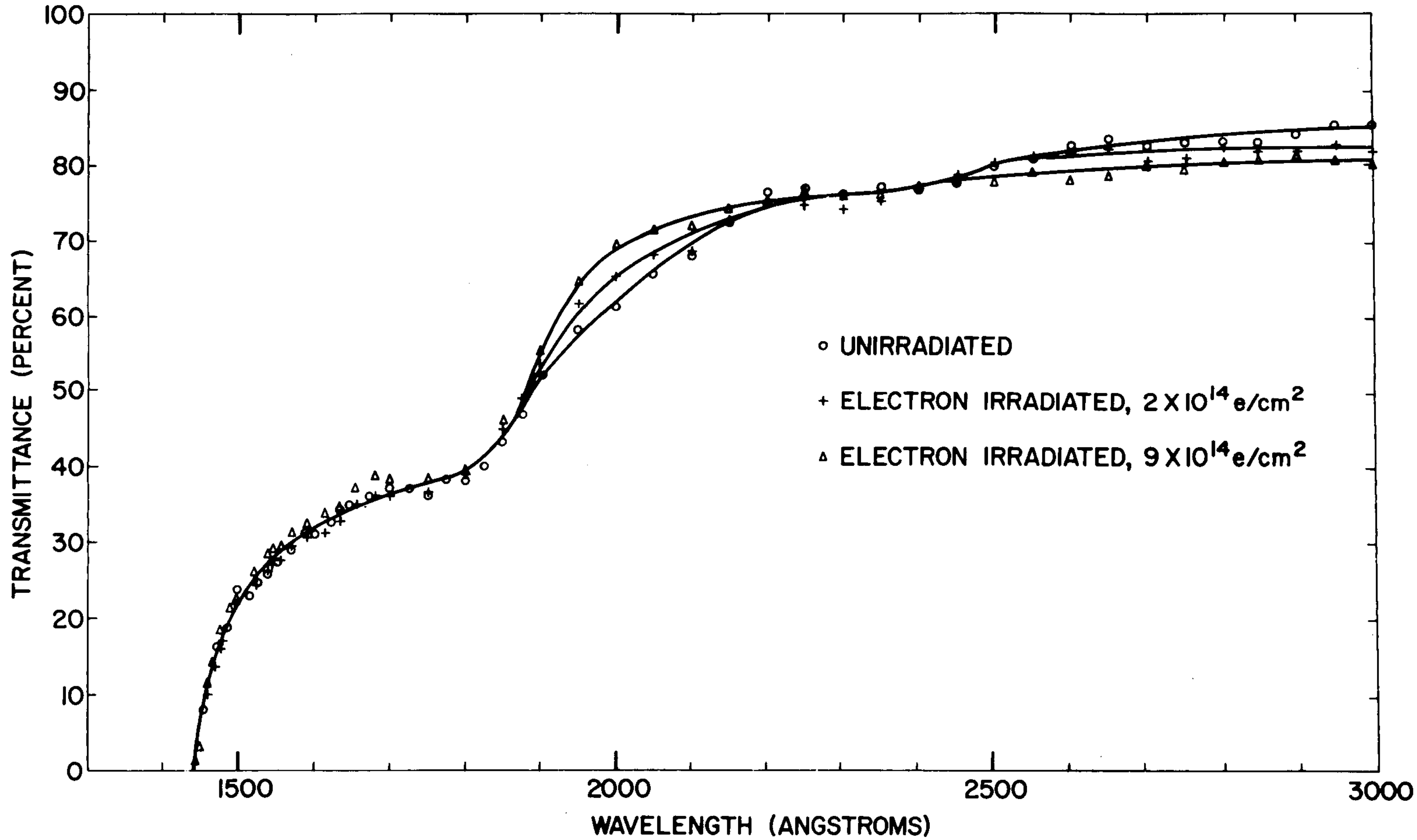

Figure 5–Transmittance of Al_2O_3 before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev and at 2.0 mev, and after irradiation by 2×10^{14} e/cm^2 at 1.0 mev and 7×10^{14} e/cm^2 at 2.0 mev

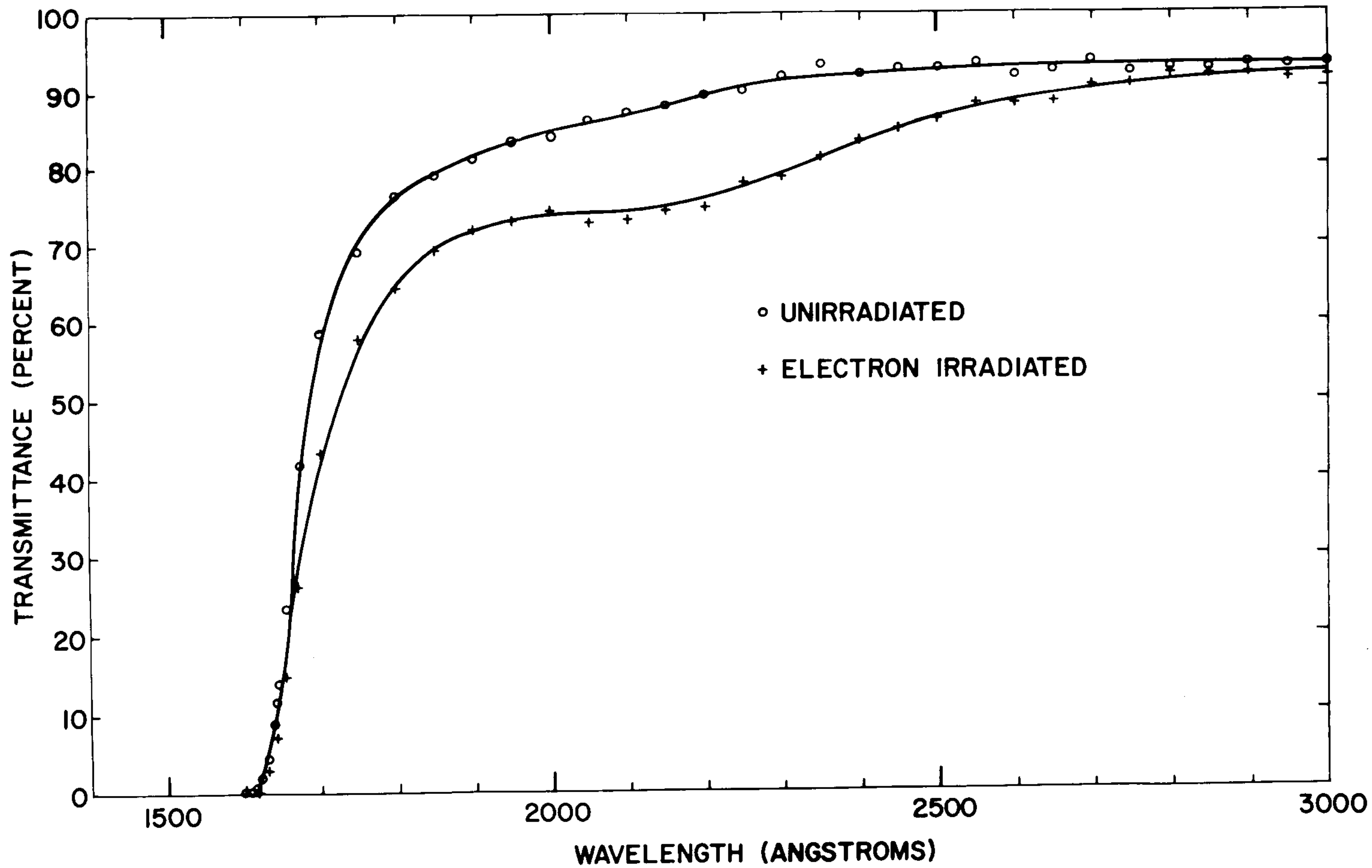

Figure 6–Transmittance of fused SiO_2 before, and after irradiation by 10^{14} e/cm^2 at 1.0 mev, and at 2.0 mev

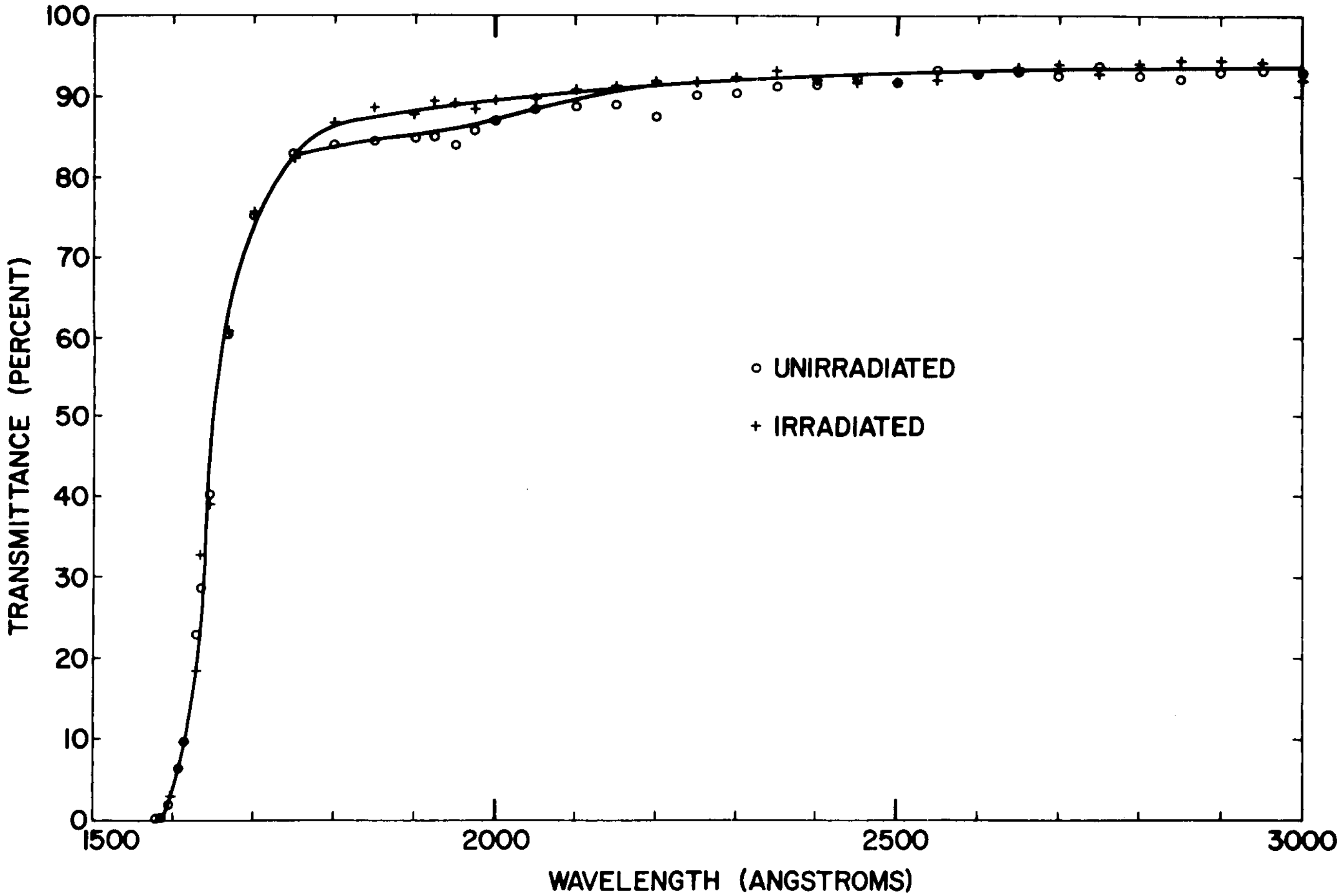

Figure 7–Transmittance of Corning 7940 fused SiO_2 before, and after irradiation resulting from 10^{14} e/cm^2 incident on a sapphire shield

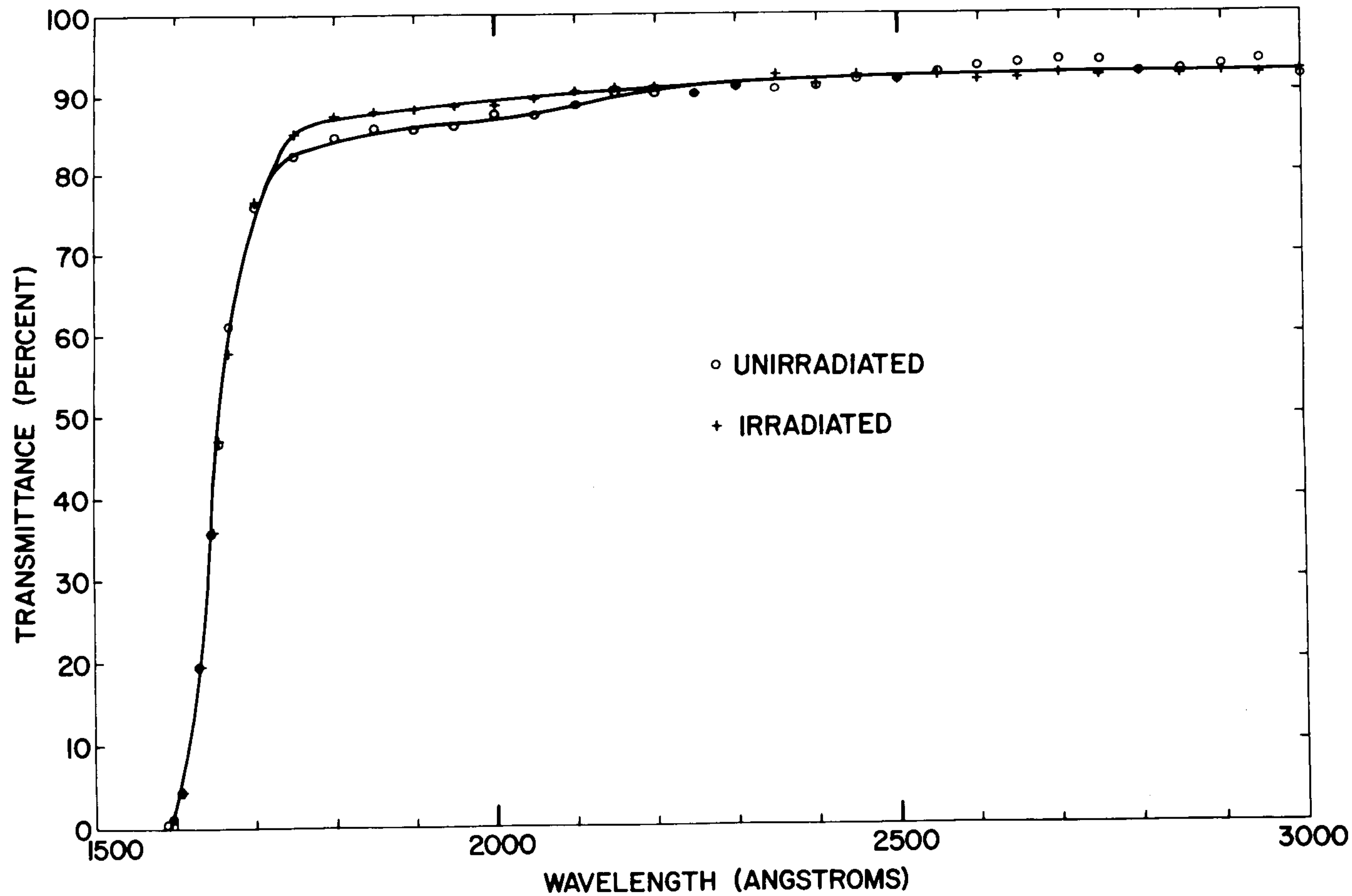

Figure 8–Transmittance of Dynasil 1850A fused SiO_2 before, and after irradiation resulting from 10^{14} e/cm^2 at 2.0 mev incident on a sapphire shield

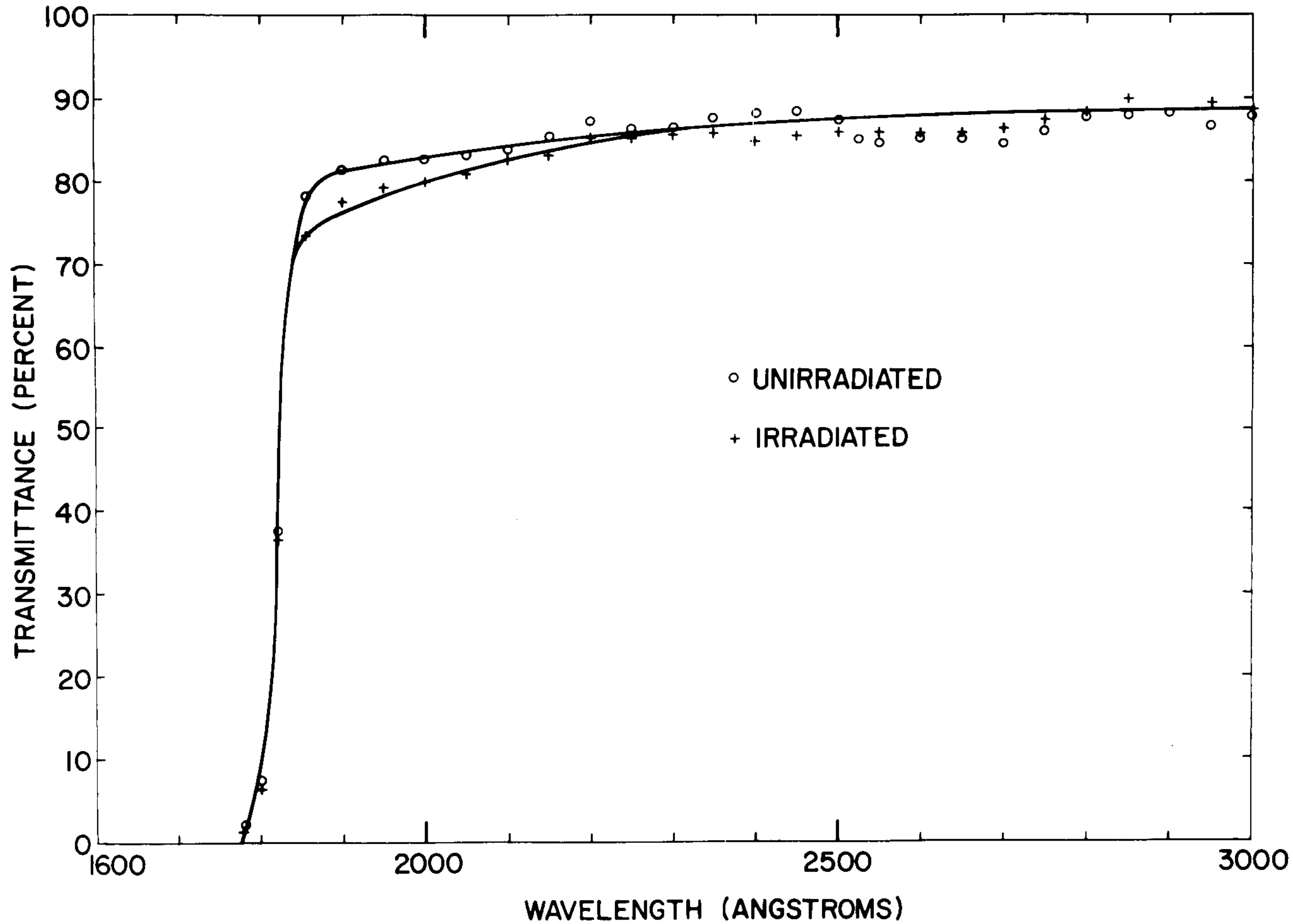

Figure 9–Transmittance of ADP before, and after irradiation resulting from irradiation resulting from 10^{14} e/cm^2 at 2.0 mev incident on a sapphire shield

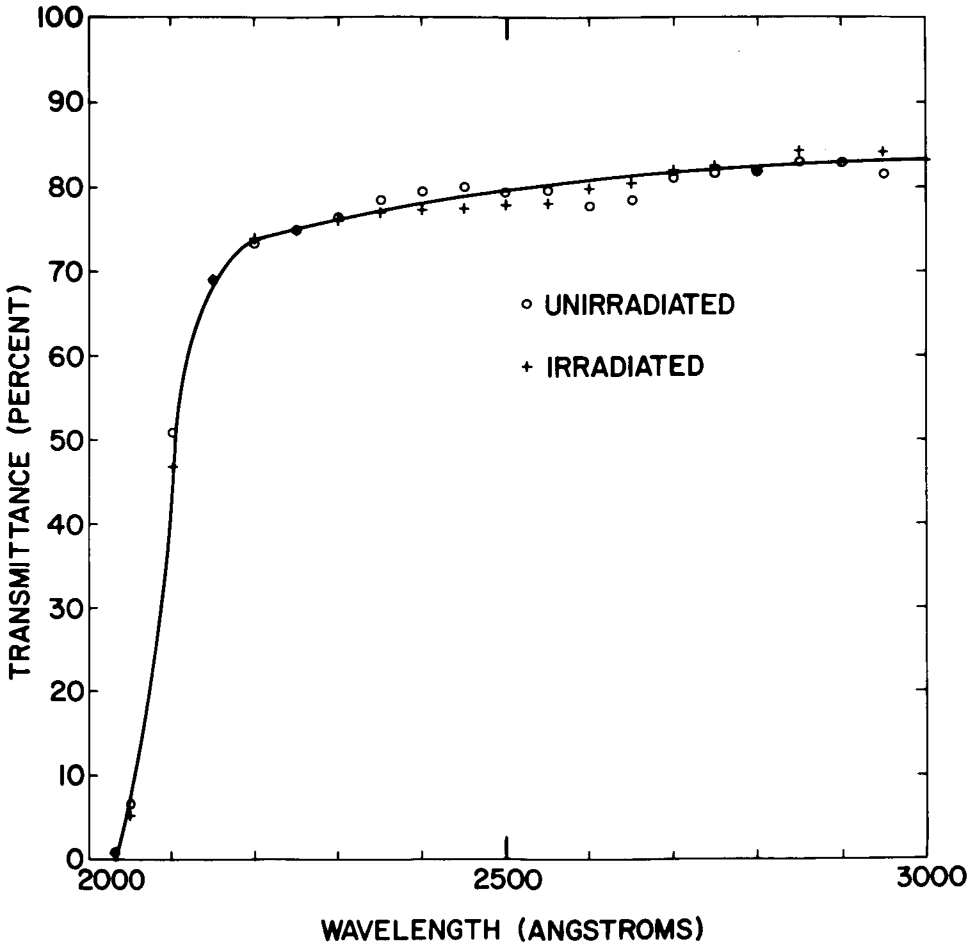

Figure 10–Transmittance of calcite before, and after irradiation resulting from 10^{14} e/cm^2 at 2.0 mev incident on a shappire shield

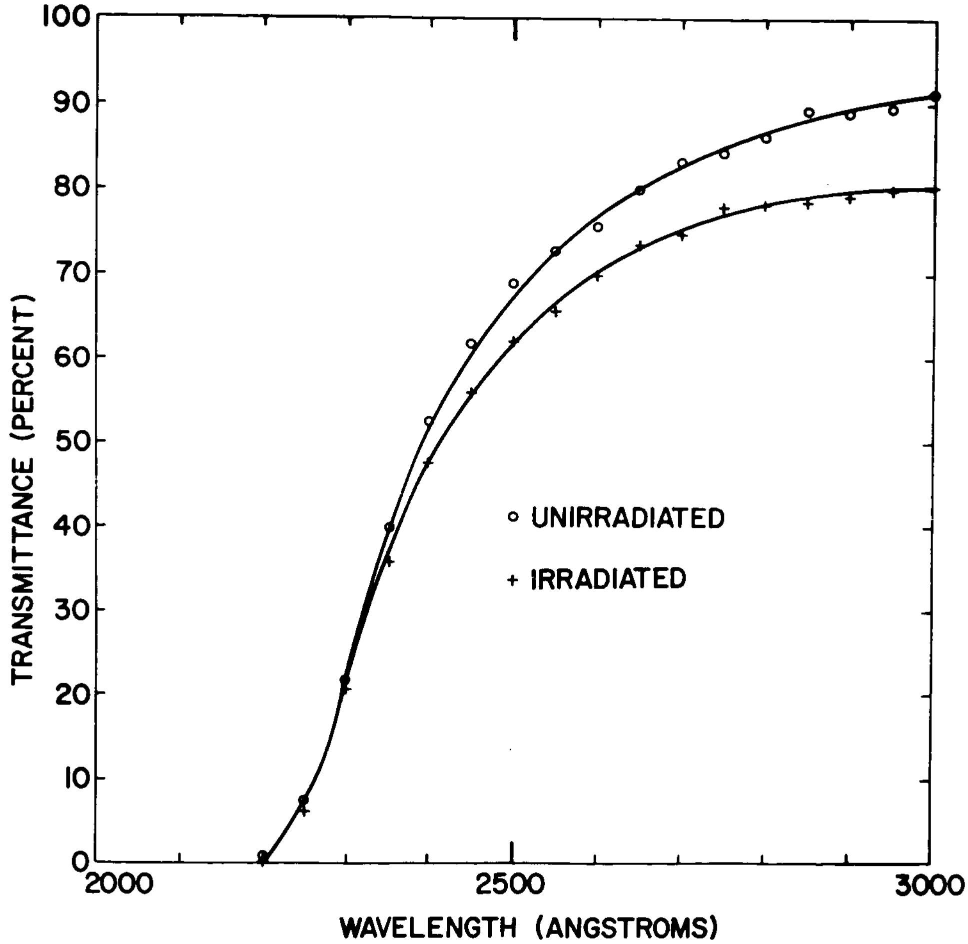

Figure 11—Transmittance of Corning 9-54 (Vycor) before, and after irradiation resulting from 10^{14} e/cm^2 at 2.0 mev incident on a sapphire shield

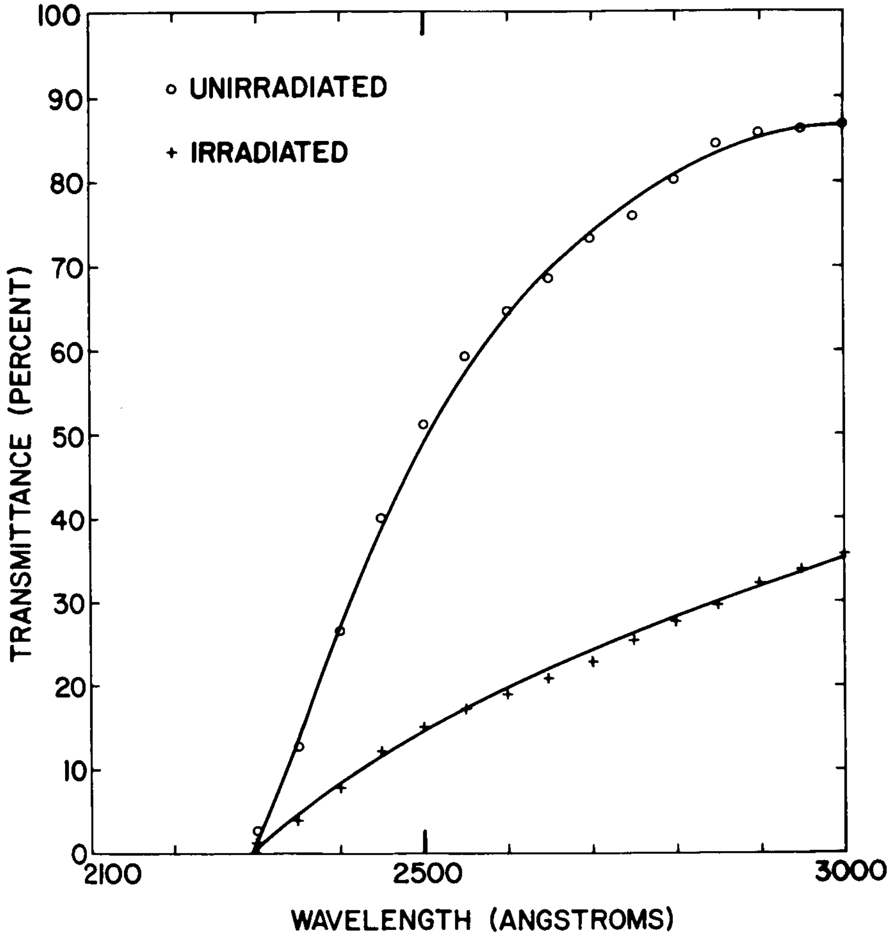

Figure 12–Transmittance of Corning 7-54 before, and after irradiation resulting from 10^{14} e/cm^2 at 2.0 mev incident on a shappire shield